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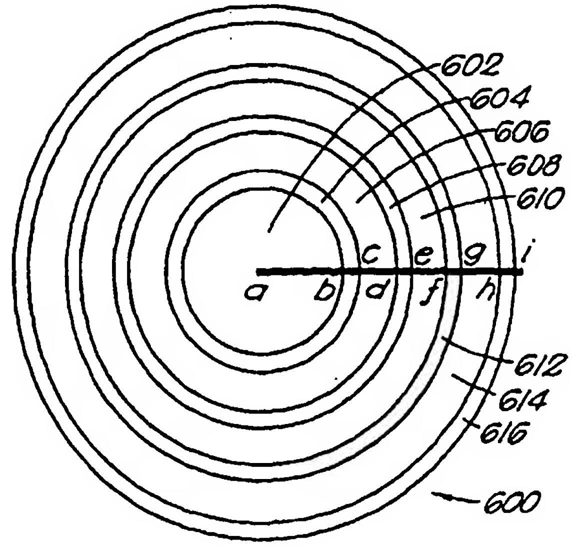
(54) Title: OMNIDIRECTIONAL MULTILAYER DEVICE FOR OPTICAL WAVEGUIDING

(57) Abstract

A device having at least one dielectric inner core region in which electromagnetic radiation is confined, and at least two dielectric outer regions surrounding the inner core region, each with a distinct refractive index. The outer regions confine electromagnetic radiation within the inner core region. The refractive indices, the number of outer regions, and thickness of the outer regions result in a reflectivity for a planar geometry that is greater than 95 % for angles of incidence ranging from 0° to at least 80° for all polarizations for a range of wavelengths of the electromagnetic radiation. In exemplary embodiments, the inner core region is made of a low dielectric material, and the outer regions include alternating layers of low and high dielectric materials. In one aspect of the invention, the device is a waveguide, and in another aspect the device is a microcavity. One embodiment describes a polystyrene-tellurium multilayer coating for the infrared and it is used on a hollow waveguide.



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OMNIDIRECTIONAL MULTILAYER DEVICE FOR OPTICAL WAVEGUIDING

PRIORITY INFORMATION

This application claims priority from provisional application Ser. No. 60/104,153 filed October 14, 1998.

BACKGROUND OF THE INVENTION

The invention relates to the field of optical waveguiding, and in particular to an omnidirectional multilayered device for enhanced waveguiding of electromagnetic radiation.

Mirrors are probably the most prevalent of optical devices. Known to the ancients and used by them as objects of worship and beauty, mirrors are currently employed for imaging, solar energy collection and in laser cavities. Their intriguing optical properties have captured the imagination of scientists as well as artists and writers.

One can distinguish between two types of mirrors, the age-old metallic, and more recent dielectric. Metallic mirrors reflect light over a broad range of frequencies incident from arbitrary angles, i.e., omnidirectional reflectance. However, at infrared and optical frequencies, a few percent of the incident power is typically lost due to absorption. Multilayer dielectric mirrors are used primarily to reflect a narrow range of frequencies incident from a particular angle or particular angular range. Unlike their metallic counterparts, dielectric reflectors can be extremely low loss.

The ability to reflect light of arbitrary angle of incidence for all-dielectric structures has been associated with the existence of a complete photonic bandgap, which can exist only in a system with a dielectric function that is periodic along three orthogonal directions. In fact, a recent theoretical analysis predicted that a sufficient condition for the achievement of omnidirectional reflection in a periodic system with an interface is the existence of an overlapping bandgap regime in phase space above the light cone of the ambient media.

The theoretical analysis is now extended to provide experimental realization of a multilayer omnidirectional reflector operable in infrared frequencies. The structure is made of thin layers of materials with different dielectric constants (polystyrene and tellurium) and combines characteristic features of both the metallic and dielectric mirrors.

It offers metallic-like omnidirectional reflectivity together with frequency selectivity and low-loss behavior typical of multilayer dielectrics.

SUMMARY OF THE INVENTION

Accordingly, in accordance with the invention there is provided a device having at least one inner core region in which electromagnetic radiation is confined, and at least two outer regions surrounding the inner core region, each with a distinct refractive index. The outer regions confine electromagnetic radiation within the inner core region. The refractive indices, the number of outer regions, and thickness of the outer regions result in a reflectivity for a planar geometry that is greater than 95% for angles of incidence ranging from 0° to at least 80° for all polarizations for a range of wavelengths of the electromagnetic radiation. In exemplary embodiments, the inner core region is made of a low dielectric material, and the outer regions include alternating layers of low and high dielectric materials. In one aspect of the invention, the device is a waveguide, and in another aspect the device is a microcavity.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified block diagram of an exemplary embodiment of a multilayer periodic dielectric film structure in accordance with the invention;

FIG. 2A is a graph of the projected band structure of a multilayer film with a light line and Brewster line, exhibiting a reflectivity range of limited angular acceptance; FIG. 2B is a graph of the projected band structure of a multilayer film together with the light line and Brewster line, showing an omnidirectional reflectance range at the first and second harmonic;

FIG. 3 is a graph of the range to midrange ratio for the fundamental frequency range of omnidirectional reflection plotted as contours;

FIG. 4 is a series of graphs showing the calculated (solid line) and measured (dashed line) reflectance (%) as a function of wavelength for TM and TE modes at normal, 45°, and 80° angles of incidence, thus showing an omnidirectional reflectivity band;

FIG. 5 is a table showing that ξ is a monotonically increasing function of the incident angle for the TM mode of an omnidirectional reflector;

FIG. 6A is a simplified block diagram cross section of an exemplary structure;

FIG. 6B is a corresponding cross section radial index of refraction profile of the structure in FIG. 6A; and

FIG. 7 is a cross section of a simplified schematic diagram of a coextrusion assembly in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 is a simplified block diagram of an exemplary embodiment of a multilayer periodic dielectric film structure 100 in accordance with the invention. The structure is made of an array of alternating dielectric layers 102,104 coupled to a homogeneous medium, characterized by n_0 (such as air with $n_0 = 1$), at the interfaces. Electromagnetic waves are incident upon the multilayer film from the homogeneous medium. The possibility of omnidirectional reflectivity for such a system has now been recognized. h_1 and h_2 are the layer thickness , and n_1 and n_2 are the indices of refraction of the respective layers 104 and 102.

An exemplary incident wave has a wave vector $\vec{k} = k_x\hat{e}_x + k_y\hat{e}_y$ and frequency of $\omega = c|k|$. The wave vector together with the normal to the periodic structure 100 defines a mirror plane of symmetry that allows distinguishing between two independent electromagnetic modes: transverse electric (TE) modes and transverse magnetic (TM) modes. For the TE mode, the electric field is perpendicular to the plane, as is the magnetic field for the TM mode. The distribution of the electric field of the TE mode (or the magnetic field in the TM mode) in a particular layer within the stratified structure can be written as a sum of two plane waves traveling in opposite directions. The amplitudes of the two plane waves in a particular layer α of one cell are related to the amplitudes in the same layer of an adjacent cell by a unitary 2x2 translation matrix $U^{(\alpha)}$.

General features of the transport properties of the finite structure can be understood when the properties of the infinite structure are elucidated. In a structure with infinite number of layers, translational symmetry along the direction perpendicular to the layers leads to Bloch wave solutions of the form

$$E_K(x,y) = E_K(x)e^{iKx}e^{ik_y y}, \tag{1}$$

where $E_K(x)$ is periodic, with a period of length a, and K is the Bloch wave number given by

$$K = \frac{i}{a} ln\left(\frac{1}{2} Tr\left(U^{(\alpha)}\right) \pm \left(\frac{1}{4}\left(Tr\left(U^{(\alpha)}\right)\right)^2 - 1\right)^{1/2}\right). \qquad (2)$$

Solutions of the infinite system can be propagating or evanescent, corresponding to real or imaginary Bloch wave numbers, respectively. The solution of Eq. 2 defines the band structure for the infinite system, $\omega(K,k_y)$.

It is convenient to display the solutions of the infinite structure by projecting the $\omega(K,k_y)$ function onto the $\omega - k_y$ plane. FIGs. 2A and 2B are examples of such projected structures.

FIG. 2A is a graph of the projected band structure of a multilayer film with a light line 200 and Brewster line 202, exhibiting a reflectivity range of limited angular acceptance with $n_1 = 2.2$ *and* $n_2 = 1.7$, and a thickness ratio of $h_2 / h_1 = 2.2 / 1.7$.

FIG. 2B is a graph of the projected band structure of a multilayer film together with the light line 204 and Brewster line 206, showing an omnidirectional reflectance range at the first and second harmonic. The film parameters are $n_1 = 4.6$ and $n_2 = 1.6$ with a thickness ratio of $h_2 / h_1 = 1.6 / 0.8$. These parameters are similar to the actual polymer-tellurium film parameters measured in the experiment.

The area 208 and 210 (light gray) highlight phase space where K is strictly real, i.e., regions of propagating states. The area 212 (white) represents regions containing evanescent states. The areas 214 and 216 represent omnidirectional reflectance ranges.

The shape of the projected band structures for the multilayer film structure can be understood intuitively. At $k_y = 0$ the bandgap for waves travelling normal to the layers is recovered. For $k_y > 0$, the bands curve upward in frequency. As $k_y \rightarrow \infty$, the modes become largely confined to the slabs with the high index of refraction and do not couple between layers (and are therefore independent of k_x).

For a finite structure, the translational symmetry in the directions parallel to the layers is preserved, hence k_y remains a conserved quantity. In the direction perpendicular to the layers, the translational symmetry no longer exists. Nevertheless, the K-number, as defined in Eq. 2, is still relevant, because it is determined purely by the dielectric and structural property of a single bilayer. In regions where K is imaginary, the electromagnetic field is strongly attenuated. As the number of layers is increased, the transmission coefficient decreases exponentially, while the reflectivity approaches unity.

Since the primary interest is in waves originating from the homogeneous medium external to the periodic structure, the focus will be only on the portion of phase space lying above the light line. Waves originating from the homogeneous medium satisfy the condition $\omega \geq ck_y / n_0$, where n_0 is the refractive index of the homogeneous medium, and therefore they must reside above the light line. States of the homogeneous medium with $k_y = 0$ are normal incident, and those lying on the $\omega = ck_y / n_0$ line with $k_x = 0$ are incident at an angle of 90°.

The states in FIG. 2A that are lying in the restricted phase space defined by the light line 200 and that have a (ω, k_y) corresponding to the propagating solutions (gray areas 208) of the structure can propagate in both the homogeneous medium and in the structure. These waves will partially or entirely transmit through the film. Those with (ω, k_y) in the evanescent regions (white areas 212) can propagate in the homogeneous medium, but will decay in the structure. Waves corresponding to this portion of phase space will be reflected off the structure.

The multilayer system leading to FIGs. 2A represents a structure with a limited reflectivity cone since for any frequency one can always find a k_y vector for which a wave at that frequency can propagate in the structure, and hence transmit through the film. For example, a wave with $\omega = 0.285\ 2\pi c/a$ (dashed horizontal line 218) will be reflected for a range of k_y values ranging from 0 (normal incidence) to $0.285\ 2\pi/a$ (90° incidence) in the TE mode, while in the TM mode it begins to transmit at a value of $k_y = 0.187\, 2\pi/a$ (~41° incidence). The necessary and sufficient criterion for omnidirectional reflectivity at a given frequency is that there exist no transmitting states of the structure inside the light cone. This criterion is satisfied by frequency ranges 214 and 216 in FIG. 2B. In fact, the system leading to FIG. 2B exhibits two omnidirectional reflectivity ranges.

A necessary condition for omnidirectional reflectivity is that light from outside of the structure cannot be allowed to access the Brewster angle $\theta_B = tan^{-1}(n_1 / n_2)$ of the multilayer structure because at this angle, the TM mode will be transmitted through. This condition is met when the Brewster line lies outside of the light line, or, terms of the refractive indices of the layers, $sin^{-1}(n_0 / n_2) < \theta_B$. A sufficient condition is the existence of a particular frequency at which no propagating mode within the crystal exists between $k_y = 0$ and $k_y = \omega / c$.

FIG. 2A is an example of a structure, which does not have an omnidirectional reflectivity range even though its Brewster crossing is inaccessible to light coming from the homogeneous medium (the Brewster crossing lies outside of the light cone). This is due to the large group velocity of modes in the lower band edge of the TM mode which allow every frequency to couple to a propagating state in the crystal. This should be contrasted with FIG. 2B, which exhibits an omnidirectional reflectivity range (area 214). The high indices of refraction actually allow for the opening of an additional omnidirectional reflectivity range (area 216) in the higher harmonic as well.

The omnidirectional range is defined from above by the normal incidence band edge $\omega_h(k_x = \pi / a,\ k_y = 0)$ (point 220), and below by the intersection of the top of the TM allowed band edge with the light line $\omega_l(k_x = \pi / a,\ k_y = \omega_l / c)$ (point 222).

The exact expression for the band edges is

$$\frac{1+\Lambda}{2} cos\left(k_x^{(1)}h_1 + k_x^{(2)}h_2\right) + \frac{1-\Lambda}{2} cos\left(k_x^{(1)}h_1 - k_x^{(2)}h_2\right) + 1 = 0, \qquad (3)$$

where $k_x^{(\alpha)} = \sqrt{(\omega n_\alpha / c)^2 - k_y^2}$ $(\alpha = 1, 2)$ and

$$\Lambda \equiv \begin{cases} \frac{1}{2}\left(\frac{k_x^{(2)}}{k_x^{(1)}} + \frac{k_x^{(1)}}{k_x^{(2)}}\right) & TE, \\ \frac{1}{2}\left(\frac{n_1^2 k_x^{(2)}}{n_2^2 k_x^{(1)}} + \frac{n_2^2 k_x^{(1)}}{n_1^2 k_x^{(2)}}\right) & TM. \end{cases} \qquad (4)$$

A dimensionless parameter used to quantify the extent of the omnidirectional reflection range is the range to midrange ratio defined as $(\omega_h - \omega_l) / \frac{1}{2}(\omega_h + \omega_l)$. Fig. 3 is a plot of this ratio as a function of n_2 / n_1 and n_1 / n_0 where ω_h and ω_l are determined by solutions of Eq. 3 with quarter wave layer thickness, and $n_1 > n_2$. The contours in this figure represent various equi-omnidirectional ranges for different material index parameters and could be useful for design purposes. The ratio for the exemplary materials is approximately 45% ($n_1 / n_2 = 2.875$, $n_2 / n_0 = 1.6$), and it is located at the intersection of the dashed lines at point 300.

It may also be useful to have an approximate analytical expression for the extent of the gap. This can be obtained by setting $cos\left(k_x^{(1)}h_1 - k_x^{(2)}h_2\right) \equiv 1$ in Eq. 3. It is found that for a given incident angle θ_0, the approximate width in frequency is

$$\Delta\omega(\theta_0) = \frac{2c}{h_1\sqrt{n_1^2 - n_0^2\sin^2\theta_0} + h_2\sqrt{n_2^2 - n_0^2\sin^2\theta_0}}\left[\cos^{-1}\left(-\sqrt{\frac{\Lambda-1}{\Lambda+1}}\right) - \cos^{-1}\left(\sqrt{\frac{\Lambda-1}{\Lambda+1}}\right)\right]. \quad (5)$$

At normal incidence there is no distinction between TM and TE modes. At increasingly oblique angles the gap of the TE mode increases, whereas the gap of the TM mode decreases. In addition, the center of the gap shifts to higher frequencies. Therefore, the criterion for the existence of omnidirectional reflectivity can be restated as the occurrence of a frequency overlap between the gap at normal incidence and the gap of the TM mode at 90°. Analytical expressions for the range to midrange ratio can be obtained by setting

$$\omega_h = \frac{2c}{h_2 n_2 + h_1 n_1}\cos^{-1}\left(-\left|\frac{n_1 - n_2}{n_1 + n_2}\right|\right),$$
$$\omega_l = \frac{2c}{h_2\sqrt{n_2^2 - 1} + h_1\sqrt{n_1^2 - 1}}\cos^{-1}\left(\left|\frac{n_1^2\sqrt{n_2^2 - 1} - n_2^2\sqrt{n_1^2 - 1}}{n_1^2\sqrt{n_2^2 - 1} + n_2^2\sqrt{n_1^2 - 1}}\right|\right). \quad (6)$$

Moreover, the maximum range width is attained for thickness values that are not equal to the quarter wave stack though the increase in bandwidth gained by deviating from the quarter wave stack is typically only a few percent.

In general, the TM mode defines the lower frequency edge of the omnidirectional range. An example can be seen in FIG. 2B for a particular choice of the indices of refraction. This can be proven by showing that

$$\left.\frac{\partial\omega}{\partial k_y}\right|_{TM} \geq \left.\frac{\partial\omega}{\partial k_y}\right|_{TE} \quad (7)$$

in the region that resides inside the light line. The physical reason for Eq. 7 lies in the vectorial nature of the electric field. In the upper portion of the first band the electric field concentrates its energy in the high dielectric regions.

Away from normal incidence the electric field in the TM mode has a component in the direction of periodicity. This component forces a larger portion of the electric field into the low dielectric regions. The group velocity of the TM mode is therefore enhanced. In contrast, the electric field of the TE mode is always perpendicular to the direction of periodicity and can concentrate its energy primarily in the high dielectric region.

A polystyrene-tellurium (PS-Te) materials system was chosen to demonstrate omnidirectional reflectivity. Tellurium has a high index of refraction and low loss

characteristics in the frequency range of interest. In addition, its relatively low latent heat of condensation together with the high glass transition temperature of the PS minimizes diffusion of Te into the polymer layer. The choice of PS, which has a series of absorption peaks in the measurement range, demonstrates the competition between reflectivity and absorption that occurs when an absorption peak is located in the evanescent state region. The Te(0.8μm) and PS (1.65μm) films were deposited sequentially to create a nine-layer film.

A $0.8 \pm 0.09\mu m$ thick layer of tellurium (99.99+%, Strem Chemicals) was vacuum evaporated at 10^{-6} torr and 7A (Ladd Industries 30000) onto a NaCl 25mm salt substrate (polished NaCl window, Wilmad Glass). The layer thickness and deposition rate were monitored in-situ using a crystal thickness monitor (Sycon STM100). A 10% solution of polystyrene (Goodyear PS standard, 110,000g/mol) in toluene was spin cast at 1000RPM onto the tellurium coated substrate and allowed to dry for a few hours, the polymer layer thickness is $1.65 \pm 0.09\mu m$. The nine layer film sequence was Te/PS/Te/PS/Te/PS/Te/PS/Te.

The optical response of this particular multilayer film was designed to have a high reflectivity region in the 10 to 15μm range for any angle of incidence (in the experiment we measure from 0° to 80°). The optical response at oblique angles of incidence was measured using a Fourier Transform Infrared Spectrometer (Nicolet 860) fitted with a polarizer (ZnS SpectraTech) and an angular reflectivity stage (VeeMax by SpectraTech). At normal incidence, the reflectivity was measured using a Nicolet Infrared Microscope. A freshly evaporated aluminum mirror was used as a background for the reflectance measurements.

FIG. 4 is a series of graphs showing the calculated (solid line) and measured (dashed line) reflectance (%) as a function of wavelength for TM and TE modes at normal, 45°, and 80° angles of incidence, thus showing an omnidirectional reflectivity band. FIG. 4 illustrates the good agreement between the calculated and measured reflectance spectra. The calculations were done using the transfer matrix method described in F. Abeles, Ann. De Physique 5, 706 (1950), incorporated herein by reference, using the film parameters.

The regimes of high reflectivity at the different angles of incidence overlap, thus forming a reflective range of frequencies for light of any angle of incidence. The frequency location of the omnidirectional range is determined by the layer thickness and

can be tuned to meet specifications. The range is calculated from Eq. 6 to be 5.6μm and the center wavelength is 12.4μm corresponding to a 45% range to midrange ratio shown in dashed lines in FIG. 3 for the experimental index of refraction parameters. These values are in agreement with the measured data. The calculations are for lossless media and therefore do not predict the PS absorption band at ~13 and 14 microns. The PS absorption peak is seen to increase at larger angles of incidence for the TM mode, and decrease for the TE mode.

The physical basis for this phenomena lies in the relation between the penetration depth and the amount of absorption. The penetration length is $\xi \propto Im(1/K)$, with K the Bloch wave number. It can be shown that ξ is a monotonically increasing function of the incident angle for the TM mode of an omnidirectional reflector, and is relatively constant for the TE mode. Thus, the TM mode penetrates deeper into the structure at increasing angles of incidence and is more readily absorbed, as is shown in the table of FIG. 5. The magnitude of the imaginary part of the Bloch wave number for a mode lying in the gap is related to its distance from the band edges. This distance increases in the TE mode due to the widening of the gap at increasing angles of incidence and decreases in the TM mode due to the shrinking of the gap.

The PS-Te structure does not have a complete photonic bandgap. Its omnidirectional reflectivity is due instead to the restricted phase space available to the propagating states of the system. The materials and processes were chosen for their low cost and applicability to large area coverage. In addition to omnidirectionality, the measurements show that a polymer, while lossy in the infrared, can still be used for reflection applications without a considerable sacrifice of performance. The possibility of achieving omnidirectional reflectivity itself is not associated with any particular choice of materials and can be applied to many wavelengths of interest. The structure of the invention offers metallic-like omnidirectional reflectivity for a wide range of frequencies, and at the same time is of low loss. In addition, it allows the flexibility of frequency selection.

In accordance with the invention, the confinement of light in cavities and wave guides using an omnidirectional multilayer film will now be described. The multilayer film structure has been described in co-pending applications Ser. Nos. 09/253,379 filed February 19, 1999 and 09/267,854 filed March 12, 1999, of common assignee, and incorporated herein by reference. Specifically, a method is presented for creating very

low loss broad band optical fibers, which are capable of transmitting around sharp bends. In addition, a design is presented for improving the delivering power of a near field optical fiber tip.

FIG. 6A is a simplified block diagram cross section of an exemplary structure 600. FIG. 6B is a corresponding cross section radial index of refraction profile of the structure 600. The structure consists of concentric cylindrical layers 604-616 with alternating indices of refraction n_1, n_2 centered on a core 602 of low dielectric material n_0, such as air. The radius of the core is h_0 and the layer thicknesses are h_1, h_2. Note that an exemplary embodiment would involve each layer consisting of different material and corresponding different layer thickness. The parameters of the multilayer film are chosen such that light from any incident angle and polarization is completely reflected by the multilayer for the range of signal frequencies.

For example, for values of n_0, n_1, n_2, h_1, and h_2 as in FIG. 2B, light can be guided for any frequency within the two broadband omnidirectional reflection ranges 214 and 216. As is generally the case, the electromagnetic radiation will be multi-mode or single-mode depending on the size of the region in which it is confined. Thus, within each broadband range the electromagnetic radiation can be multi-mode or single mode depending on the size of the inner core region. For large core radii, the light will be multi-mode and for very small radii the light will be single mode.

Conventional optical fibers confine a propagating EM pulse by total internal reflection where the electromagnetic (EM) wave travels through a high index fiber core surrounded by low-index cladding. In accordance with the invention, the method of confinement in the Omniguide™ waveguide structure is the polarization independent omnidirectional reflectance of EM waves at the walls of the hollow fiber. The advantages of this mode of confinement are numerous.

There is very low loss associated with material absorption since the wave travels essentially through air, which is extremely low loss when compared with any dense medium. This enables low loss propagation which is of importance in basically every device that involves light guiding for communication, lasers and more.

Conventional optical communication fibers need amplification to compensate for absorption losses in the material, and to this end, the fiber is periodically doped with erbium. The use of erbium severely limits the bandwidth of the fiber. Since the structure of the invention is very low loss and does not need amplification, orders of magnitude

increase in the usable bandwidth is possible. In addition, the omnidirectional multilayer structure provides a strong confinement mechanism and will propagate signals around very sharp bends as demonstrated in other systems with strong confinement mechanisms.

Such a multilayer coated fiber will also be important for improving the delivering power of a fiber tip in a near-field scanning optical microscope. The tip is used to deliver optical power with a spot size far smaller than the wavelength of light. Metal coating is currently employed in order to confine light to such a small length scale. Metal coatings have material absorption losses, which in this case limits the maximum delivery power. The fiber tip with a multilayer coating overcomes this problem since it is essentially lossless.

The ultimate goal is to create a hollow structure with walls made of a multilayer coating in accordance with the structure described heretofore. The structure may be of, but is not limited to, a cylindrical geometry. One method to produce such a structure is to take a thin wall hollow fiber made of glass or polymer and coat it with alternating layers of dielectrics. The layers could be made of a polymer or glass as the low refractive index component, and Germanium or Tellurium as the high index material. One would then take the fiber and evaporate a layer of prescribed thickness using a thermal evaporator or sputtering device. The subsequent low index layer would be deposited by dipping the fiber in a dilute solution of the polymer, or by evaporating a monomer followed by a rapid polymerization.

Another exemplary method would be the coextrusion of the entire structure using a combination of immiscible polymers, one loaded with a high index component in a fine powder form the other without additives as in FIG. 7. FIG. 7 is a cross section of a simplified schematic diagram of a coextrusion assembly 700 in accordance with the invention. An extruding device 702 provides a structure 704 of alternating layers of high and low index polymer surrounding an air core 706.

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:

CLAIMS

1. A device comprising:

at least one dielectric inner core region in which electromagnetic radiation is confined; and

at least two outer dielectric regions surrounding the inner core region, each with a distinct refractive index, said outer regions confining electromagnetic radiation within said inner core region, wherein

the refractive indices, the number of outer regions, and thickness of the outer regions result in a reflectivity for a planar geometry that is greater than 95% for angles of incidence ranging from 0° to at least 80° for all polarizations for a range of wavelengths of said electromagnetic radiation.

2. The device of claim 1, wherein said device comprises a circular cross section.

3. The device of claim 1, wherein said device comprises a rectangular cross section.

4. The device of claim 1, wherein said device comprises a triangular cross section.

5. The device of claim 1, wherein said device comprises a hexagonal cross section.

6. The device of claim 1, wherein said inner core region comprises a low dielectric material.

7. The device of claim 6, wherein said inner core region comprises a gas.

8. The device of claim 7, wherein said inner core region comprises air.

9. The device of claim 1, wherein the outer regions comprise alternating layers of low and high dielectric materials.

10. The device of claim 9, wherein said low dielectric material comprises a polymer or a glass.

11. The device of claim 9, wherein said high dielectric material comprises germanium or tellurium.

12. The device of claim 1, wherein the outer regions comprise alternating layers of dielectric and thin metal materials.

13. The device of claim 1, wherein said inner core region has dimensions on the order of the wavelength of said electromagnetic radiation.

14. The device of claim 1, wherein said inner core region has dimensions larger than the wavelength of said electromagnetic radiation.

15. The device of claim 1, wherein said device is utilized to guide high power electromagnetic radiation.

16. The device of claim 1, wherein said device is utilized to guide high power electromagnetic radiation around bends.

17. The device of claim 1, wherein said device is utilized to guide electromagnetic radiation in at least one broadband region.

18. The device of claim 1, wherein said device is utilized to guide electromagnetic radiation in a plurality of broadband region.

19. The device of claim 18, wherein the electromagnetic radiation in said broadband regions is single mode.

20. The device of claim 18, wherein the electromagnetic radiation in said broadband regions is multi-mode.

21. The device of claim 1, wherein said device is utilized as a microcavity to confine electromagnetic radiation.

22. A waveguide which exhibits omnidirectional reflection, comprising:

at least one inner core region in which light is confined; and

at least two outer regions surrounding the inner core region, each with a distinct refractive index, said outer regions confining light within said inner core region, wherein

the refractive indices, the number of outer regions, and thickness of the outer regions result in a reflectivity for a planar geometry that is greater than 95% for angles of incidence ranging from 0° to at least 80° for all polarizations for a range of wavelengths of said light.

23. A microcavity comprising:

at least one inner core region in which light is confined; and

at least two outer regions surrounding the inner core region, each with a distinct refractive index, said outer regions confining light within said inner core region, wherein

the refractive indices, the number of outer regions, and thickness of the outer regions result in a reflectivity for a planar geometry that is greater than 95% for angles of incidence ranging from 0° to at least 80° for all polarizations for a range of wavelengths of said light.

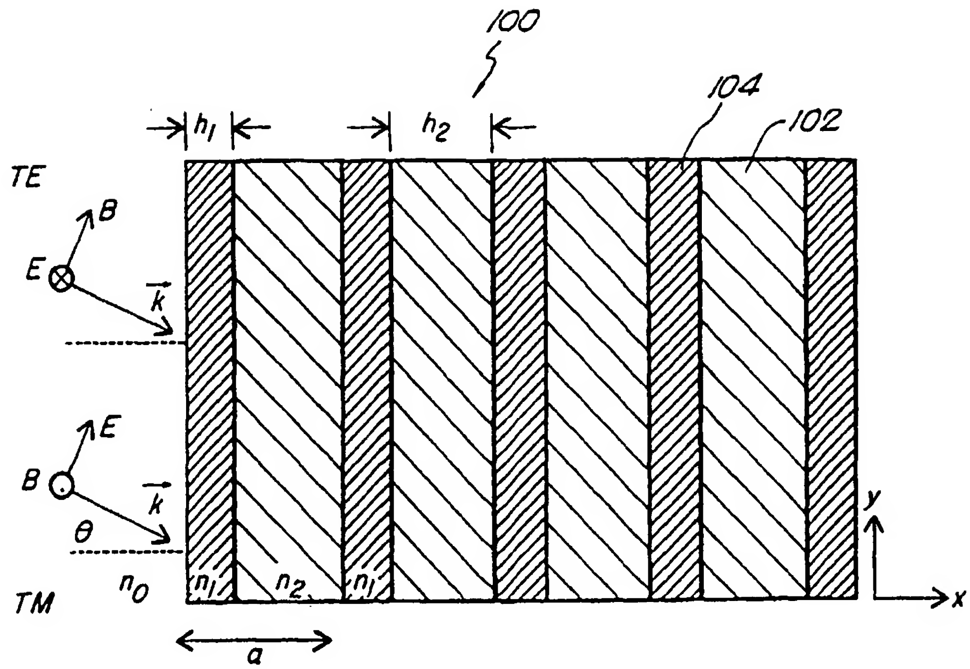

FIG. 1

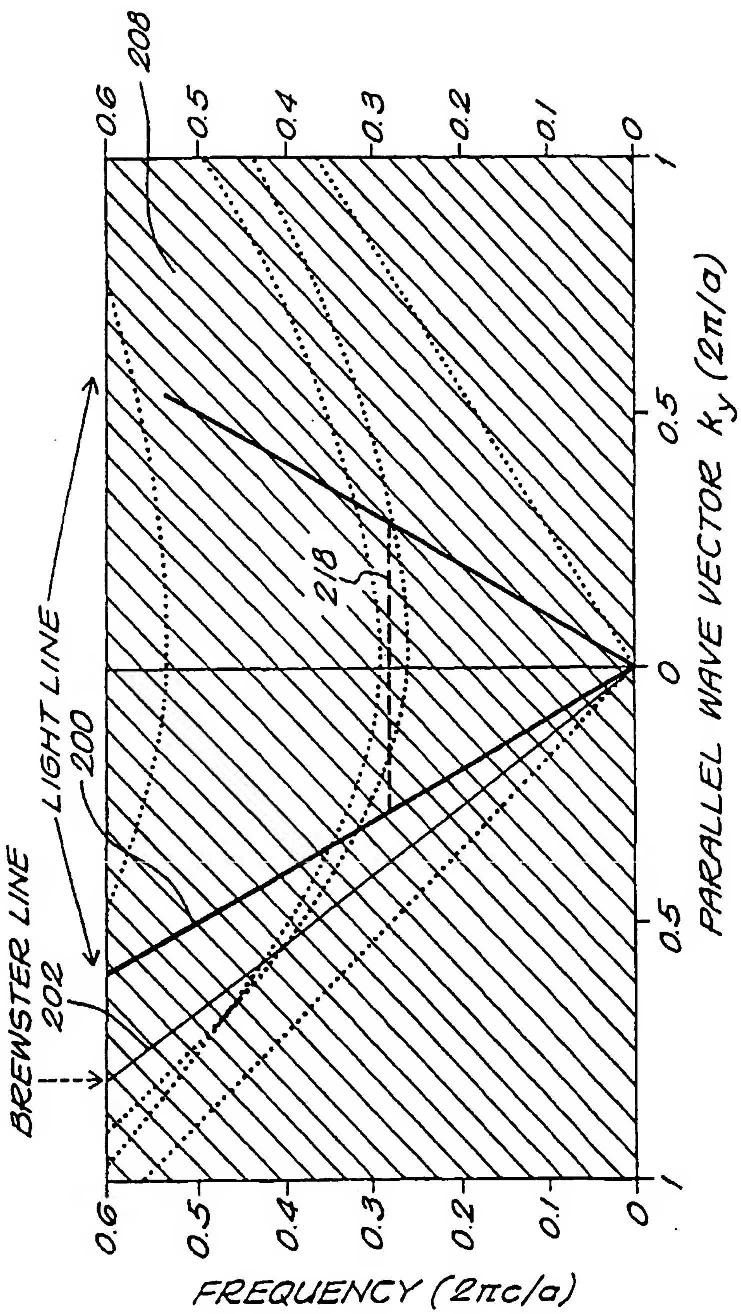
BREWSTER LINE
202
LIGHT LINE
200
208
218
0.6
0.5
0.4
0.3
0.2
0.1
0
1
0.5
0
0.5
1
PARALLEL WAVE VECTOR k_y (2π/a)
FREQUENCY (2πc/a)

FIG. 2A

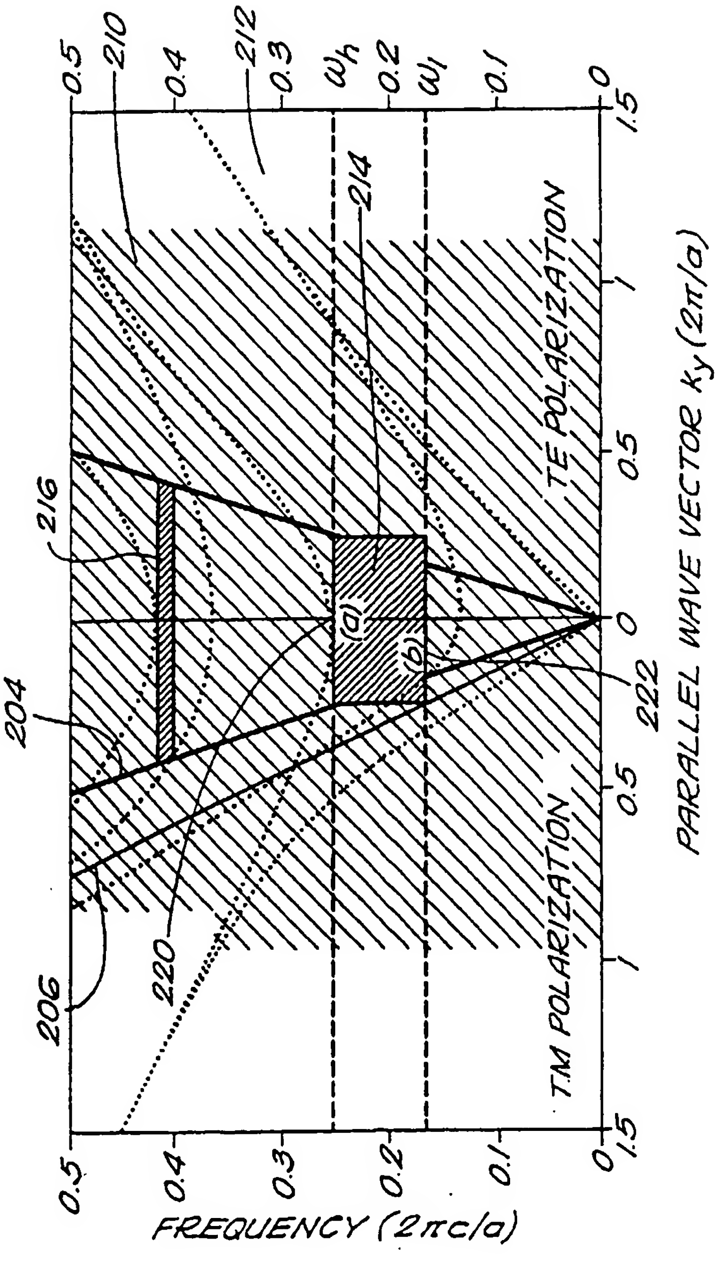
TE POLARIZATION
TM POLARIZATION
PARALLEL WAVE VECTOR k_y (2π/a)
FREQUENCY (2πc/a)
ω_h
ω_l
(a)
(b)
204
206
210
212
214
216
220
222

FIG. 2B

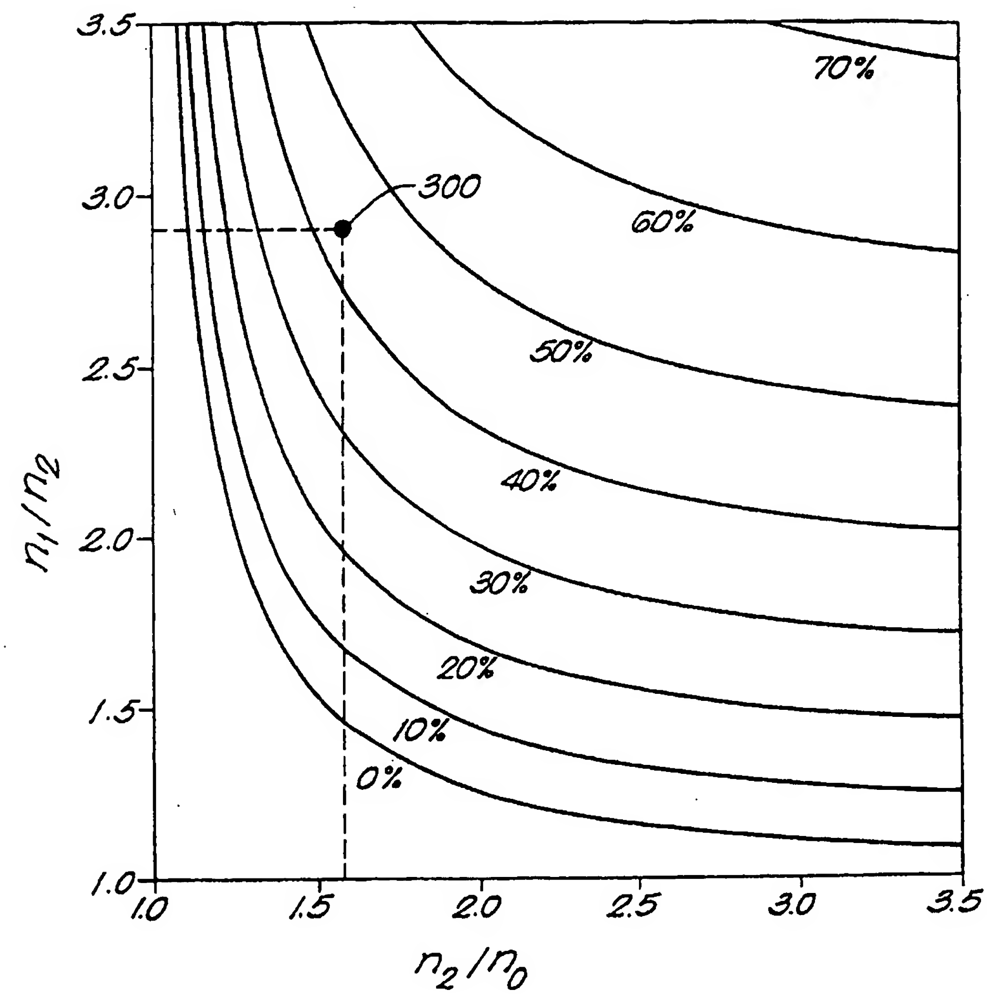
3.5
3.0
2.5
2.0
1.5
1.0
1.0
1.5
2.0
2.5
3.0
3.5
n1/n2
n2/n0
300
70%
60%
50%
40%
30%
20%
10%
0%

FIG. 3

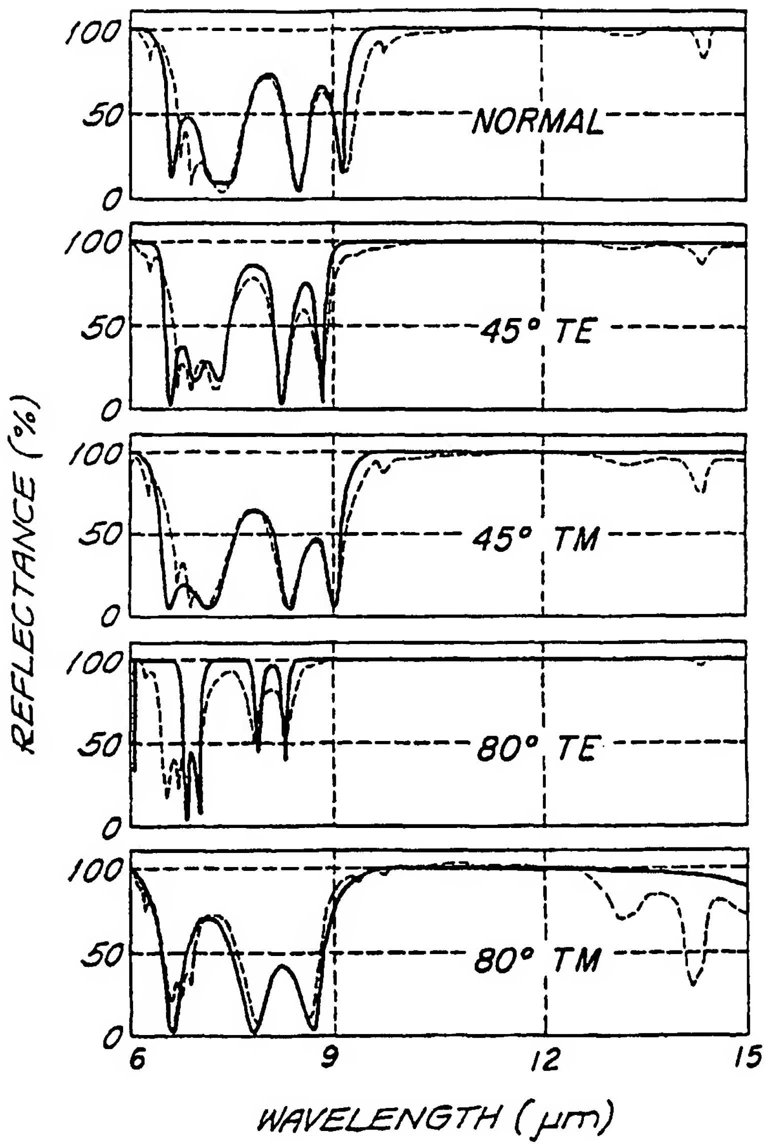
100
50
0
NORMAL
45° TE
45° TM
80° TE
80° TM
REFLECTANCE (%)
6
9
12
15
WAVELENGTH (μm)

FIG. 4

ANGLE OF INCIDENCE (DEGREES)	ξ_{TM} (μm)	ξ_{TE} (μm)
0	2.51	2.51
45	3.05	2.43
80	4.60	2.39

FIG. 5

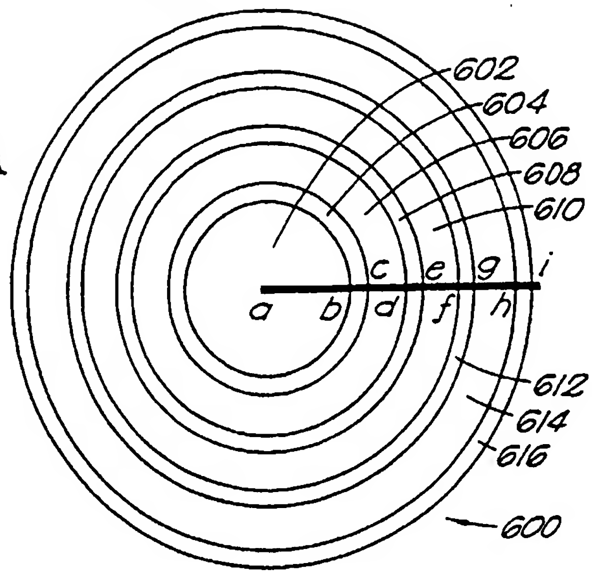

FIG. 6A

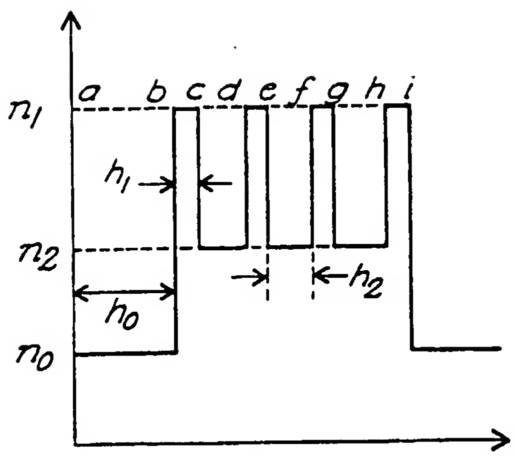

FIG. 6B

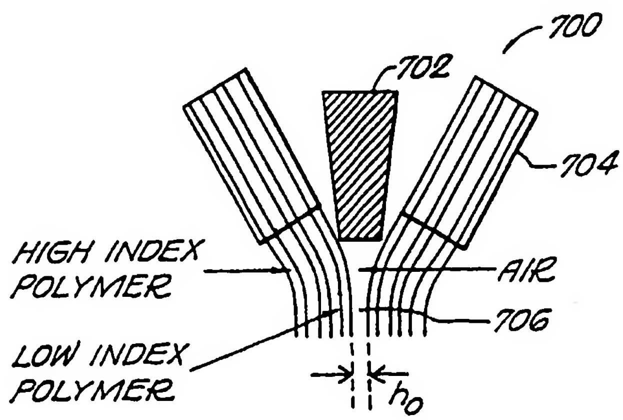

FIG. 7

INTERNATIONAL SEARCH REPORT

Int ional Application No
PCT/US 99/23833

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/20 G02B6/10 G02B5/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B F21V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97 01774 A (MINNESOTA MINING & MFG) 16 January 1997 (1997-01-16) page 3, line 15 - line 21 page 6, line 11 - line 21 page 7, line 23 -page 8, line 6 page 11, line 1 - line 3 page 14, line 26 -page 15, line 23 page 19, line 20 - last line; figure 8 page 21, line 1 - line 5 page 24, line 30 -page 25, line 11 page 27, line 21 -page 28, line 16; figure 13 ---	1-10,12, 14-23

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 February 2000	01/03/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Ciarrocca, M

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/23833

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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X	WO 94 09393 A (COHERENT INC) 28 April 1994 (1994-04-28) abstract page 10, line 13 -page 13, line 19 page 17, line 34 -page 18, line 22; figure 8 ---	1,3,6-9, 12,14-23
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Information on patent family members

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			DE	3751454	D	14-09-1995
			DE	3751454	T	15-02-1996
			DE	3778181	A	21-05-1992
			EP	0234233	A	02-09-1987
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			DE	69327478	D	03-02-2000
			EP	0729591	A	04-09-1996
			JP	8502598	T	19-03-1996
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